



Technology Projections for Solar Dynamic Power

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Abstract. Solar Dynamic power systems can offer many potential benefits to Earth orbiting satellites including high solar-to-electric efficiency, long life without performance degradation, and high power capability. A recent integrated system test of a 2 kilowatt SD power system in a simulated space environment has successfully demonstrated technology readiness for space flight. Conceptual design studies of SD power systems have addressed several potential mission applications: a 10 kilowatt LEO satellite, a low power Space Based Radar, and a 30 kilowatt GEO communications satellite. The studies show that with moderate component development, SD systems can exhibit excellent mass and deployed area characteristics. Using the conceptual design studies as a basis, a SD technology roadmap was generated which identifies the component advances necessary to assure SD systems a competitive advantage for future NASA, DOD, and commercial missions.

BACKGROUND

Solar Dynamic (SD) power systems concentrate sunlight into a receiver where the energy is transferred to a heat engine for conversion to electrical power. As shown schematically in Figure 1, the heated fluid from the receiver is circulated through a power conversion unit where electrical power is generated from heat. The waste heat is removed through a heat exchanger and dissipated by radiator panels to space. A power management and distribution (PMAD) system converts the heat engine's electrical output as required by the spacecraft bus and maintains control of the SD system operation. The state-of-the-art power conversion technology for space SD systems is based on the closed Brayton cycle. Brayton cycle systems utilize a turbine, compressor and rotary alternator to generate electrical power using an inert gas working fluid. A recuperative heat exchanger between the turbine discharge and receiver inlet is used to improve cycle efficiency. Other power conversion technologies that could be used in SD power systems include Stirling and Rankine cycles. Generally, SD systems are considered to offer the benefits of high solar-to-electric efficiency, long life without performance degradation, and high power capability. Long life is made possible through the use of non-contacting gas bearings, hermetic sealing of the gas circuit, redundant electronic components, and ultraviolet/atomic oxygen protective coatings on all optical surfaces. Radiation degradation is reduced relative to solar photovoltaic arrays since semi-conducting materials are not used on the large exposed surfaces.

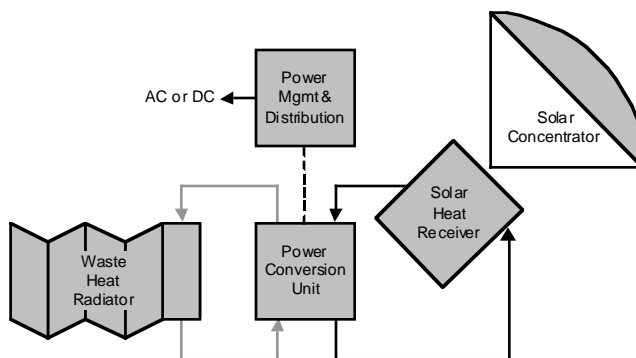


FIGURE 1. Solar Dynamic Power System Schematic.



FIGURE 2. Solar Dynamic Ground Test Demonstration at NASA Lewis.

Solar Dynamic Ground Test Demonstration

A Ground Test Demonstration (GTD) of a 2 kW SD space power system, shown in Figure 2, was recently completed at the NASA Lewis Research Center. The test included an off-axis solar concentrator, heat receiver with thermal energy storage (TES), recuperated-Brayton cycle heat engine, and waste heat radiator in a thermal vacuum environment. The TES, a LiF-CaF₂ phase change material contained in canisters surrounding the gas flow tubes, was used to heat the working fluid during the eclipse to allow continuous power production through the orbit, eliminating the need for rechargeable batteries. The testing was conducted with a solar simulator to provide a complete solar-to-electrical system demonstration. Cycle efficiencies (ratio of alternator power to heat input) of the Brayton unit were measured at 29% and orbital efficiencies (ratio of electrical energy output to solar energy collected over an orbit) were measured at 17%. From 1994 to 1998, the system had accumulated nearly 800 hours of operation including 33 ambient start-ups and 372 orbit cycles (Shaltens, 1999).

A flight version of the 2 kW system, which utilized a similar receiver and Brayton engine to the ground test system and a Russian designed concentrator and radiator, was planned for 1998 but was cancelled due to Shuttle manifest changes. A significant portion of the flight receiver, engine, and controls were completed prior to the project's cancellation and some of the flight development hardware was integrated with the GTD testbed for performance characterization. Allied Signal Aerospace Systems Equipment, Tempe, Arizona served as prime contractor for both the GTD and Flight Demonstration projects.

TECHNOLOGY ROADMAP

Currently, there are no specific programs in SD technology development. However, there are related programs in advanced solar concentrators and high efficiency heat engines. The solar concentrator efforts are supported through the Air Force Research Laboratory (AFRL) Solar Orbit Transfer Vehicle (SOTV) project. SOTV is a flight experiment of a solar thermal propulsion system. Advanced concentrator development is aimed at high efficiency, lightweight, deployable systems using either inflatable or spline radial panel (SRP) technology. The major companies involved in concentrator development include SRS Technologies in Huntsville, Alabama and Harris Corporation in Melbourne, Florida. An associated project, Advanced Solar Concentrator Technology (ASCoT), has been proposed as a piggy-back experiment on SOTV to further develop the optics

system of a solar thermal propulsion system using a refractive secondary concentrator in tandem with an inflatable fresnel primary.

Free-piston Stirling convertors are being pursued as an advanced power conversion system for various NASA and DOD missions. Advanced, high efficiency engine development is being leveraged from terrestrial power programs. Stirling Technology Company (STC) in Kennewick, Washington has successfully designed, built, and operated free-piston convertors at 10 watts and 350 watts. STC is also developing a 55 watt Technology Demonstration Convertor (TDC), to be used in a four engine configuration, as an alternative power conversion system for the Advanced Radioisotope Power System (ARPS) project (White, 1999). All of these engines share common technology characteristics including flexure bearings. The 10 watt engine has undergone endurance testing to over 45,000 hours. A key technical hurdle, parallel engine operation with thermodynamically independent convertors, has been demonstrated with the 350 watt STC engines. Another technical objective, dynamic vibration compensation, is already being addressed through a Small Business Innovation Research (SBIR) grant with STC. In addition, the Applied Research Laboratory at Penn State University expects to demonstrate a combined Stirling and flywheel system in a breadboard configuration for a future U.S. Navy application.

The SD GTD test program demonstrated the performance potential of SD systems but did not address the weight goals needed to compete with advanced solar photovoltaic and battery systems. The program elements of a mass competitive SD power system development would include 1) a lightweight, deployable solar concentrator (already being addressed in the SOTV program), 2) a sodium heat pipe, heat receiver with LiF phase change material, and 3) a lightweight, composite radiator. The advanced concentrator, either inflatable or SRP, reduces the areal density of the SD concentrator by a factor of five from 10 kg/m² for conventional rigid panel concentrators to less than 2 kg/m². Both concentrator technologies also provide reduced stowage volume and autonomous deployment. A heat pipe receiver with LiF TES reduces the specific weight of a SD heat receiver by a factor of two from 10 kg/kWt for conventional tube and canister receivers with LiF-CaF₂ to less than 5 kg/kWt. Heat pipe receivers also allow higher cavity flux levels, and greater flux variation easing the pointing/surface accuracy requirements of the concentrator. A modest increase in the peak cycle temperature from 1033 K to 1100 K accompanies the change from LiF-CaF₂ to LiF TES. A composite radiator reduces the areal density of the SD heat rejection system by a factor of two from 12 kg/m² for conventional aluminum panels to 6 kg/m².

An additional program element, particularly suited to lower power requirements, is free-piston Stirling energy conversion. Free-piston Stirling convertors utilize a power piston, displacer, and linear alternator to produce electrical power using a high pressure, inert gas working fluid. The use of Stirling rather than Brayton, has the combined effect of increasing conversion cycle efficiency and increasing the effective radiator temperature, resulting in a smaller concentrator and radiator.

Cost Projections

The Design, Development, Test and Engineering (DDT&E) costs associated with the SD component advances described previously, were estimated based on contractor rough-order-of-magnitude (ROM) quotes. The cost quotes were based on a 2 kW system, but are applicable up to about 7 to 10 kW. The total DDT&E costs for developing all the major SD components was between \$9M and \$14M depending on concentrator and heat engine technology. Due to the suitability of SD components to mass production, low system recurring costs are also projected. The SRP concentrator, representing the highest component cost at \$6M, was twice the cost of a thin film, inflatable concentrator (\$3M). The large variation is the result of a cost versus risk trade-off. The SRP structure and deployment system is expected to have less development risk due to its similarity to RF antenna systems already being built for commercial applications. Alternatively, inflatable concentrators, which are projected to be less expensive and easier to fabricate, have never been fully demonstrated and therefore present a somewhat greater development risk. The heat pipe receiver (\$4M) and composite radiator (\$2M) efforts would draw heavily from technology development from the 1980's. The Stirling costs, projected at \$2M, represent the funding required to take a commercial, terrestrial engine which has already been developed and modify it for space. A ground test of the advanced development components as an integrated system would be desirable to verify system performance prior to a flight hardware production. The test could be conducted in the large solar-thermal/vacuum facility used for the SD GTD system testing.

MISSION CASE STUDIES

In order to quantify the performance benefits of these advanced components, several mission case studies were devised. The LEO mission is meant to represent the class of satellite being considered for either NASA Earth science or broadband communications. The low power SBR mission is based on the Discoverer II satellite under development by the Air Force, DARPA, and NRO. The high power GEO mission is intended to represent the next generation of global digital communications satellites. All of the studies included a thermodynamic optimization of the heat engine efficiency for minimum system mass. The optimization represents a trade-off of heat source mass (concentrator and receiver) versus radiator mass. Higher efficiency results in a smaller heat source, but lower heat rejection temperature which leads to larger radiators. Lower efficiency yields a high heat rejection temperature to reduce radiator size at the expense of a larger heat source. The overall system mass includes the concentrator, receiver, heat engine, radiator, and PMAD to supply 120 Vdc to the spacecraft bus.

LEO Mission

Future NASA and commercial satellites planned for LEO are expected to range in power from 100's of watts up to 10 kW. The use of electric propulsion for station keeping or orbit insertion may increase power levels. Examples of planned LEO satellites include the NASA EOS AM-1 and PM-1 satellites at 2.5 kW and 5 kW, respectively and the Teledesic broadband satellite system, estimated at 6 to 10 kW per satellite.

Table 1 shows the projected performance of a 10 kW SD power system for a 500 km circular LEO with a 95 minute orbit period and 36 minute eclipse. The SD system includes TES for continuous sun/eclipse power production and a 10 year system life was assumed. The reference, state-of-the-art (SOA) system assumes a rigid concentrator, tube and canister receiver with LiF-CaF₂ TES, and an aluminum panel radiator. The addition of an advanced concentrator in case 1A provides a 40% increase in specific power. The optimized cycle efficiency is lower with the reduction in the relative mass of the heat source, but accompanies a decrease in the radiator area. Further reduction in the heat source mass is realized with the introduction of an advanced, heat pipe receiver and LiF TES as shown in case 1B. The specific power improves an additional 40% and the total deployed area (concentrator and radiator) is reduced by 15%, relative to the reference case. Case 1C shows that a SD Brayton system with all advanced components can achieve a system specific mass approaching 12 W/kg. The use of free-piston Stirling conversion with the advanced components, in case 1D, improves the specific power to 15 W/kg while reducing the deployed area by 25% relative to the all-advanced Brayton case.

Space Based Radar Mission

There are several different concepts for Earth orbital Space Based Radar (SBR) missions. Discoverer II is a relatively low power radar demonstration of Synthetic Aperture Radar (SAR) and Ground Moving Target Indication (GMTI). A two satellite demonstration in 2003 is planned as a precursor to a 24-48 satellite objective system in the 2007 to 2010 timeframe. The planned orbit altitude is 770 km which relates to a 100 minute orbit period and a 35 minute maximum eclipse, and the system design life is 7 to 10 years.

TABLE 1. SD Performance for 10 kW LEO Mission.

Case	Ref	1A	1B	1C	1D
Concentrator	SOA	Advanced	Advanced	Advanced	Advanced
Receiver	SOA	SOA	Advanced	Advanced	Advanced
Radiator	SOA	SOA	SOA	Advanced	Advanced
Power Conversion	Brayton	Brayton	Brayton	Brayton	Stirling
Cycle Efficiency	32.7%	30.4%	30.3%	33.8%	42.0%
Concentrator (m ²)	61.9	61.3	62.5	56.8	50.9
Radiator (m ²)	33.5	28.6	21.0	25.9	11.7
System Mass (kg)	1984	1415	1028	870	665
Specific Power (W/kg)	5.0	7.1	9.7	11.5	15.0

TABLE 2. SD Performance for Low Power Space Based Radar.

Case	Ref	2A	2B	2C
Concentrator	SOA	Advanced	Advanced	Advanced
Receiver	SOA	Advanced	Advanced	Advanced
Radiator	SOA	Advanced	Advanced	Advanced
Power Conversion	Brayton	Brayton	Brayton	Stirling
Peak Power Source	TES	TES	Flywheels	Flywheels
Cycle Efficiency	31.4%	31.3%	24.4%	36.3%
Concentrator (m ²)	18.9	17.8	9.8	7.6
Radiator (m ²)	10.1	7.6	3.1	1.6
System Mass (kg)	689	361	275	129
Specific Power (W/kg)	1.2	2.3	3.1	6.5

Most SBR missions share a common characteristic power profile. Power levels are low for the majority of the orbit while the satellite is in standby mode. When the satellite acquires a target, the power requirements increase for radar operation. While the Discoverer II mission requirements are still evolving, early power estimates indicate a 400 watt standby level and 4.8 kW peak during radar operation. The radar duty cycle is estimated at 10% or approximately 10 minutes per orbit, resulting in an orbit average power of 850 watts.

The projected performance of SD-based power systems for the Discoverer II mission are presented in Table 2. The first two cases assume the use of TES to satisfy the radar peak requirement. This approach requires the concentrator and radiator be sized for the peak power demand and the SD power conversion system adjust to load power changes through speed or gas inventory control. As before, the reference case assumes a rigid concentrator, tube and canister receiver with LiF-CaF₂, and an aluminum panel radiator. Specific power, defined as the ratio of average orbital power to total power system mass, is only 1.2 W/kg as a result of the oversized system. Case 2A shows the expected performance of an all advanced component Brayton with LiF TES, providing a nearly 2x increase in specific power over the reference.

An option to using TES for the radar peak is to use auxiliary energy storage to augment the SD system, such as flywheels (Christopher, 1998). In this case, the SD receiver would have sufficient TES to maintain a constant sun/eclipse power output and the flywheels would supply the additional power for the radar peak. The Discoverer II power profile would demand a 1 kW SD system for standby power and flywheel charging, and 0.65 kW-hrs of flywheels for peak power augmentation. The benefit of auxiliary energy storage is evident in case 2B, with improvements of 30% in specific power and 50% in deployed area relative to the all-advanced component Brayton/TES case. The substitution of Stirling conversion in case 2C, which is very well suited to this power level, provides a 30% reduction in deployed area and a 110% increase in specific power versus the Brayton/flywheel case. The generally poor values of specific power for all the cases are representative of the challenging power profile associated with SBR type missions.

GEO Mission

The power requirements for future GEO communications satellites are expected to reach 30 kW. Power levels continue to rise as manufacturers increase the number and size of communication transponders on each satellite to expand revenue potential. Loral and Hughes are both developing future GEO satellites to meet increasing power demands. The most difficult challenge for a GEO solar power system is satisfying the long maximum eclipse period. On a yearly basis, GEO satellites experience an increasing solar eclipse from several minutes up to a maximum of 70 minutes of the 24 hour orbit period.

The 30 kW projected demand would be best satisfied by two 15 kW SD units. The performance projections for a 15 kW, 10 year life, GEO SD power module are provided in Table 3. Similarly to the SBR mission, auxiliary energy storage was considered as an option to TES, for the eclipse period. The flywheel energy storage requirement for a 15 kW GEO power module is 17.5 kW-hrs. The reference case with SOA components and TES results in a specific power of 4.7 W/kg. The use of an advanced concentrator, receiver, and radiator in case 3A improves the specific power by more than a factor of two, but still results in an

TABLE 3. SD Performance for 15 kW GEO SD Module.

Case	Ref	3A	3B	3C
Concentrator	SOA	Advanced	Advanced	Advanced
Receiver	SOA	Advanced	Advanced	Advanced
Radiator	SOA	Advanced	Advanced	Advanced
Power Conversion	Brayton	Brayton	Brayton	Stirling
Eclipse Power Source	TES	TES	Flywheels	Flywheels
Cycle Efficiency	33.9%	35.9%	27.8%	37.0%
Concentrator (m ²)	56.5	50.3	60.8	53.1
Radiator (m ²)	54.0	45.1	27.4	10.0
System Mass (kg)	3174	1524	1150	973
Specific Power (W/kg)	4.7	9.8	13.7	16.2

unwieldy heat receiver at 722 kg (out of 1524 kg total) due to the excessive thermal energy storage requirement for eclipse. If the receiver TES were eliminated and flywheels were used for the eclipse period, system specific power for an advanced component Brayton system improves to nearly 14 W/kg. While a 15 kW power module may be somewhat large for the STC class of Stirling convertors, case 3C presents the estimated performance of a Stirling/flywheel system for GEO. As was the result for the previous Stirling cases, substantial benefits can be realized in both specific power and deployed area.

CONCLUSION

Solar dynamic systems represent the next generation of advanced space power providing long life, reduced deployed area, and high power capability. Integrated system tests have demonstrated the performance potential of SD power. Advanced component development will provide the necessary system mass improvements to assure competitiveness with other advanced power technologies. SD technology is well suited for a wide range of Earth orbiting mission applications including low, medium, and geo-synchronous Earth orbit, with and without power peaking. For a modest development investment, SD systems could achieve system specific power levels greater than 10 W/kg with Brayton conversion and greater than 15 W/kg with Stirling conversion.

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